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Dayton C. Miller

THE INFLUENCE OF THE MATERIAL OF WIND-INSTRUMENTS ON THE TONE QUALITY

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SOUND is the sensation resulting from the action of an external stimulus on the sensitive nerve apparatus of the ear; it is a species of reaction against this external stimulus, peculiar to the ear, excitable in no other organ of the body, and completely distinct from the sensations of any other sense.

Atmospheric vibration is the normal and usual means of excitement for the ear, this vibration being produced directly in some instruments, called wind-instruments, and indirectly through the vibration of elastic bodies in others, such as string and percussion instruments; and often the vibration originates in bodies not especially designed for producing sounds.

Physics is mainly concerned with the nature of the external stimulus, and the word sound is often restricted to refer only to these external stimuli. But the purely mechanical properties of these stimuli often differ among themselves differently than do the auditory effects. Our interest is largely in relation to musical sounds and hence for the present investigation we are concerned with the properties of the sounds of mechanical physics

[1] Address of the vice-president and chairman of Section B, American Association for the Advancement of Science, delivered December 29, 1908.

only in so far as they affect the ear, or produce sensation. We may, therefore, define sound substantially in the words of Helmholtz, as already given, and proceed to investigate the physical cause of these sensations.

If we investigate how many kinds of sensation the ear can generate, we find that, either because of fundamental or acquired distinctions, the ear divides sounds roughly into two main classes, noises and musical tones. Helmholtz's distinction between tone and noise, that one is periodic and the other non-periodic, in the light of recent experiments, seems hardly adequate. Analysis clearly shows that many musical tones are non-periodic, at least in the sense intended; and it is equally certain that noises are as nearly periodic as are some tones. In some instances noises are due to a rapidly changing period, causing non-periodicity; but by far the greater number of noises, which are continuous, are merely complex and only apparently irregular; their analysis is difficult or impossible. The ear, often because of lack of training, or the absence of suitable standards for comparison, or perhaps on account of fatigue, fails to appreciate the relations between certain sounds, and, resigning its attention, classes the sounds as noises. The study of noises is essential to the understanding of the qualities of musical instruments, and especially of speech; but their study may well be passed till we more completely understand the nature of the apparently simpler, and much more interesting, musical tones. While actual musical tones may be non-periodic, containing incommensurable par-

tial tones, yet it is probable that the components are individually periodic, and often the entire tone is periodic. We may proceed with the provisional definition that the sensation of tone is caused by a periodic vibration in the air, and to this we are mainly to confine our attention.

The ear, further, receives three classes of sensations from tones, and presumably no more. One of these gives rise to the characteristic of the tone called pitch; this is easily proven to depend upon a very simple condition, that of mere frequency of vibration.

The second property of tone is loudness or intensity, which is not so simple as pitch. For tones of the same pitch, it varies mainly as the energy of vibration, and this is a function of the amplitude of vibration, varying approximately as its square; loudness also varies with pitch, approximately as the square of the frequency. As regards the loudness of what we hear, very much depends upon the individual ear, and, as Professor Sabine has clearly shown, upon the surrounding objects, walls of rooms, etc.

The third property of tone is much the most complicated; it is that characteristic of sounds produced from some particular instrument or voice, by which they are distinguished from the sounds of the same loudness and pitch, produced from other instruments or voices. This characteristic is called timbre, clang-tint, *klangfarbe,* or, best of all, the idea is expressed by the simple English word quality; we shall use the word quality in this specific sense.

With comparatively little practise any

one can acquire the ability to distinguish with great ease any one of a long series of musical instruments, even when they all sound tones of the same loudness and pitch. There is an almost infinite variety of tone quality; not only do different instruments have characteristic qualities, but different individual instruments of the same family show more delicate shades of tone quality; and even notes of the same pitch can be sounded on a single instrument with qualitative variations. The bowed instruments, of the violin family, show this ability in a marked degree. But no musical instrument equals the human voice in the richness of qualitative varieties and variations; speech employs these very qualitative varieties to distinguish the letters and syllables.

When we inquire as to the cause of tone quality, since pitch depends upon frequency and loudness upon amplitude, we conclude that quality must depend upon the only remaining property of a periodic vibration, namely, the peculiar kind or form of the motion; or, if we represent the vibration by a curve or wave line, the quality is dependent upon the peculiarities represented by the shape of the wave. There is possible an endless variety of motion for the production of sound, and quality is, therefore, almost infinitely complicated in its causes, as compared with the other two properties of sounds.

There can not be a simpler mode of vibration than that known as simple harmonic motion, which is represented by the wave line called the sine curve; such motion is often referred to as pendular motion. Tuning forks properly con-

structed and mounted on resonance boxes are shown by analysis to produce vibrations in the air which are single simple harmonic motions; the resulting tones are called simple tones, and their sensation is markedly simple and pure. If several simple tones of different pitches, as from several tuning forks, are simultaneously sounded, they simultaneously excite different systems of waves, which exist as variations in density of the air; the resulting displacements, velocities, and changes in density of the air are each equal to the algebraic sum of the corresponding displacements, velocities and changes in density which each system of waves would have separately produced had it acted independently. There must, therefore, be peculiarities in the motion of a single particle of air which differ for a single tone and for a combination of tones; and in fact the kind of motion during any one period is entirely arbitrary, and may indeed be infinitely various.

The method by which the ear proceeds in its analysis of tone quality was first definitely stated by Ohm, in Ohm's law of acoustics. Helmholtz states this law in the following forms:

> All musical tones, however complex or peculiar in quality, are periodic; the human ear perceives pendular vibrations alone as simple tones, and it resolves all other periodic motions of the air into a series of pendular vibrations, *hearing* the series of simple tones which correspond to these simple vibrations.

Another rendering of this law is:

> Every motion of the air which corresponds to a composite mass of musical tones is capable of being analyzed into a sum of simple pendular vibrations, and to each such simple vibration

corresponds a simple tone, sensible to the ear, and having a pitch determined by the periodic time of the corresponding motion of the air.

The separate component tones are called partial tones, or simply partials; that partial having the lowest frequency is the fundamental, while the others are overtones. However, it sometimes happens that a partial not the lowest in frequency is so predominant as to give the main character to the whole sound, and it may be mistaken for the fundamental. If the overtones have frequencies which are exact multiples of the frequency of the fundamental, they are often called harmonics; otherwise they may be designated as inharmonic partials.

In stating his law, in 1843, Ohm says:

Fourier spread light in our darkness when he brought out (in 1822) his work "La Théorie Analytique de la Chaleur," and so enabled theoretical mechanics to solve the most difficult problems of physics with unparalleled ease.

Fourier had shown in a purely mathematical way, and with no idea of acoustical application, that any given regular periodic function can always be expanded in a trigonometric series of sines and cosines, and for each case in one single way only. Each sine or cosine term in the series may be considered as representing a single vibration; then in Fourier's series, the successive terms have frequencies which are exact multiples of the first, but the amplitudes and phase differences are arbitrary and can always be found in every given case, by peculiar methods of calculation which Fourier has shown.

So far as Fourier's theorem is concerned this method of analyzing sound vibrations

might be merely a mathematical form, not necessarily having any corresponding actual meaning in the sounds themselves. Moreover, in actual musical sounds, many of the important partials are not exact multiples of the fundamental in frequency, that is, they are inharmonic, and with these Fourier's theorem has nothing whatever to do, although Ohm's law still applies to them.

Helmholtz fully demonstrates that the ear unaided can thus analyze tones; he also developed several methods for assisting the ear, chiefly by the use of resonators. His monumental work, "Tonenempfindungen," was referred to by our chairman last year as

> produced by a masterful knowledge of physiology, physics and mathematics, and a scholar's knowledge of the literature of music, remarkable for its breadth, completeness and wealth of detail.

A large part of this work is concerned with the demonstrations of Ohm's law that the quality of a musical sound is dependent upon the particular combination of partial tones which make up the sound under examination. He held that

> Differences in musical quality of tone depend solely on the presence and strength of partial tones, and in no respect on the difference in phase under which these partial tones enter into composition.

A few historical references may be interesting as showing how clearly these ideas were perceived by the earliest investigators.

Descartes (1618) says:

> No musical sound can be heard which does not appear to the ear to be accompanied by the octave above it.

Mersenne (1636) says of Aristotle:

He seems to have been ignorant of the fact that every string produces five or more different sounds at the same time, the strongest of which is called the natural tone of the string, and alone is accustomed to be taken notice of, for the others are so feeble that they are perceptible only to delicate ears.

Perrault (1680) says:

Every noise, although apparently simple, is in effect a system and an assemblage of an infinity of partial noises that compose a total, in which no confusion is remarked on account of the affinity that all these partial noises have together.

Sauver (1702) remarks that

The organ only imitates by the combination of its stops the natural harmony of sonorous bodies.

La Grange and Bernoulli (1760) both state clearly the cause of quality:

The same single sonorous ray may be moved at the same time by many species of vibrations which do not interfere with each other in any manner; in the place of a node with regard to one species, a segment may be formed with regard to another.

Monge (1800) says that

Quality is due to the order and number of the vibrations of the aliquot parts of a string, and if the vibrations of these aliquot parts could be suppressed, all strings, of whatever material, would yield tones of the same quality.

Young (1800), describing his experiments for rendering visible the vibrations of a string by means of a ray of light, says:

According to the various modes of applying the bow an immense variety of orbits are produced; more than enough to account for all the differences of tone by different performers.

Biot (1817) says:

All sonorous bodies yield simultaneously an infinite number of sounds of gradually decreasing intensity, but the law for the series of harmonics is different for bodies of different forms; it is this

difference which produces the particular character of sound called timbre. And may not the quality of each particular substance, wood or metal, for instance, be due to the superior intensity of one or another harmonic?

Many other quotations might be given of opinions expressed by Rameau, Chladni, Wheatstone and others; but enough has been said to show that the ideas as to quality were well understood before Ohm put forth his law, which is almost misnamed.

Helmholtz (1862) defended and developed Ohm's theorem, and gave elaborate proof of it, chiefly by the use of resonators. Melde (1864) made visible, by his beautiful tuning-fork monochord, the simultaneous existence of two or more harmonic vibrations in a string. Koenig (1872) showed the simultaneous coexistence of two sets of waves in the same organ pipe by means of his manometric flames.

The theories of Ohm and Helmholtz seem so simple that they have generally been accepted as expressing the whole physical condition, and few investigators have successfully combated them. Seebeck (1844) argued that the quality of tone must be decided by the ear, and he concluded that the definition of a simple tone given by Ohm is too limited; he believes that other forms of vibration besides the pendular are capable of giving the sensations of a single simple tone, and that simple tones may have different qualities among themselves. Seebeck greatly improved the siren, and used it to produce the fundamental and partial tones with which he experimented. Helmholtz admits the experimental results of Seebeck, and after extended argument,

he claims that Seebeck did not give proper attention to the hearing of the partials.

Another investigator to oppose Helmholtz was Koenig; he was not satisfied with the statement as to the cause of tone-quality. Koenig invented the wave siren, a very beautiful piece of demonstration apparatus, with which he showed that quality is not accounted for solely by the presence and relative intensity of the partials; but that phase is a factor too important to be left out of account. If changes in the number and intensity of the partials give rise to such differences in quality as we observe in instruments belonging to different families, Koenig says the changes in the difference of phase for the same partials are competent to produce differences of quality at least as sensible as those which are noticed in instruments of the same kind.

Helmholtz says distinctly that if we disregard the noise of rushing wind, the proper musical quality of the tone produced by blowing over the mouth of a bottle is really the same as that produced by a tuning fork; and that the tone of a flute, which according to Helmholtz is practically devoid of over-tones, is the same as that of a tuning fork. Since we agree to some extent with Seebeck, that tone quality must be decided by the ear, we hesitate to adopt the conclusion that the bottle and the fork both give simple tones of the same musical quality.

When this address was first thought of, it was hoped that some conclusions might be reached regarding this general question. But, for reasons referred to later, it seems best to limit our further consideration to

certain particular instances, about which it is believed some definite conclusions can be drawn.

Perhaps the points to be investigated will be most clearly presented by a somewhat personal statement of the incidents that led to this enquiry.

In connection with the study of the flute as a musical instrument there arose the question which may be specifically stated:

Is the tone quality of a flute, the tube of which is made of gold, superior to that of a similar flute having a tube of silver or of wood? If there is a difference, what is its cause?

Probably many will be inclined at once to dismiss the subject as not a question, claiming that there can be no difference in such a case, due to material. The writer was of this opinion at one time. When visiting the establishment of an eminent London flute maker, in 1900, he was shown several flutes which were tested. One instrument seemed of such unusual excellence that the remark was made that it was certainly of the finest quality of any that had ever been tried. After the instrument had been returned to its case, the writer enquired whether it would be possible, at some time in the visit to London, for him to see one of the few gold flutes which had been made, and which were celebrated for quality. The reply was startlingly unexpected, for the maker said, with evident satisfaction, that the flute just played was of gold! It had been prepared for the Paris Exposition, but was not being exhibited, as the English exhibits had been largely withdrawn because of some French caricatures of Queen Victoria. It may be well, also, to add that the flute had been

examined in dim artificial light, the color thus escaping notice. However, the incident carried conviction to the writer, as very few tests could have done.

As further justification for considering this question, several quotations will be given showing the great difference of opinion among those who should speak with authority.

Each kind of wind instrument, except the flute, has always been made of its own proper kind of material; there are two large classes, the wood-wind and the brass-wind of the orchestra. Each group has its distinct tone quality, which is generally considered as due to the method of tone production, while the material is regarded as a matter of mechanical convenience. The flute is classified as a wood-wind instrument.

Formerly flutes were usually made of wood, though in 1806 flutes of glass were patented by Laurent, of Paris, the advantages claimed being, not tone-quality, but freedom from checking, changes of bore, and leakage. Ivory has been used for small flutes, and parts of large flutes, mainly for the sake of appearance. In 1847 Theobald Boehm, of Munich, a Royal Bavarian court-musician, who had, in 1832, invented a new system of fingering and key construction, made elaborate experiments on the bore, size of holes, and material. These experiments had an academic relationship, for they were carried out under the guidance of Dr. Carl von Schafhäutl, an eminent professor in the University of Munich, who was a life-long personal friend of Boehm. Boehm experimented with hundreds of tubes, and our

interest lies in the fact that he introduced with great success cylindrical tubes of hard-drawn silver, though wood tubes were also used. There at once arose a controversy as to the relative merits of various materials, which still rages.

Besides being one of the world's greatest artists and a composer of ability, Boehm maintained one of the most celebrated flute manufactories, and made hundreds of flutes of the highest excellence; instruments made in his lifetime are to-day valued above all others, as the old Italian violins are valued above modern instruments. Near the end of his career, in 1871, he published a book giving the results of his sixty years of experience, in which he says:

> The greater or less hardness and brittleness of the material has a very great effect upon the quality of tone. Upon this point much experience is at hand. Tubes of pewter give the softest, and at the same time the weakest, tones; those made of very hard and brittle German silver have, on the contrary, the most brilliant, but also the shrillest, tones; the silver flute is preferable because of its great ability for tone modulation and for its unsurpassed brilliancy and sonorousness; compared with these the tones of flutes made of wood, sound literally wooden.

Directly against these opinions of Boehm we may place the equally authoritative one of Victor C. Mahillon, of Brussels, the head of the celebrated musical instrument manufactory, and the Curator of the Museum of Instruments of the Belgian Royal Conservatory of Music—containing one of the most celebrated collections of musical instruments in the world. Mahillon has devoted his life to the study of musical instruments, and is recognized the world

over as an eminent authority. In his treatise, "Elements d'Acoustique, musicale et instrumentale," one of the best works on the acoustics of musical instruments, he says:

Theobald Boehm was the first, we believe, to try to construct a flute upon scientific principles, using a cylindrical tube, with rationally placed holes; it was he who first tried to explain the division of the air column of the tube. . . . It is to be regretted that this celebrated reformer of the flute was not able to grasp the principle, resulting moreover from his own theory, that the air is the only vibrating body in the flute, as well as in all other wind-instruments. It would have been better had he not written the following lines, which in our opinion, disfigure all of his work.

Mahillon then quotes Boehm's opinions given above, and continues:

One would almost refuse to believe, if it were not written, that a man of the standing of Boehm, who had revolutionized, from the foundation, the principles which had existed for ages in the construction of flutes, was not able to release himself completely from such prejudices; nevertheless, he held to this one blunder.

In another place, Mahillon says:

This error is shared in by nearly all artists who play wind instruments. The one who plays a brass instrument will say that the thinner the walls the more easy will be the production of tone; the bassoonist is persuaded that all the vibrations of his instrument exist in the material of the mouth piece.

He describes the opinion of the clarionetist and flutist at length, and continues:

Who does not know the brilliant sound of the cavalry trumpet? It would seem that if this same brilliancy were produced by an instrument constructed wholly of wood, that this error whose existence we regret, would disappear forever. But it is not so. For more than ten years, we have had occasion to make heard, almost every day, an

instrument constructed by Mr. C. Mahillon; it possesses the exact proportions of a cavalry trumpet, and gives exactly the same brilliancy as the instrument of brass, so that it is impossible to distinguish the one from the other. How much trouble professors might spare their pupils, if, being inspired by the revelations of science, they would content themselves with teaching principles, and abandon the prejudices which pass every day from master to pupil.

Albert Lavignac, professor in the Paris Conservatory of Music, in his book, "Music and Musicians," published in New York in 1899, says:

> First we have to notice that the sonorous body is the column of air contained inside the tube, whose metal, wood, or other material, has no office whatever, except that of determining the form and dimensions of the mass of air imprisoned within it, which is itself, and itself alone, the vibrating body. The recognition of this fact is of the highest importance in understanding the subject.

Lavignac then describes the experiments of Mahillon with the wood trumpet, and other experiments of the same import by Sax, the instrument maker of Paris, with brass clarionets; he also refers to pasteboard organ pipes and other instances, which support his theory.

The gentlemen quoted are by no means alone in their opinions. The writer has occasionally mentioned to some of his scientific friends that he sometimes wondered whether the tone of a flute is affected by the material of its tube. Many times the answer has been: "Of course, *you* think it is not."

In direct opposition to the experiments of Mahillon and Sax are those of Schafhäutl (of the University of Munich), who throughout his life made many researches

on acoustical subjects, being influenced, no doubt, by the problems which his friend Boehm was trying to solve. He is the author of many papers, which appeared in the *Annalen der Physik,* and in various scientific and musical journals. One of his papers, published in 1879, is entitled: "Is the dogma of the effect of the material out of which a wind-instrument is made, upon the tone of the same, a fable?" Schafhäutl quotes at length a sarcastic statement which begins by saying:

A fable, the more remarkable since it is always discussed, is that the material of which a wind-instrument is made, has an influence upon the material of the same; that this is not so rests upon incontrovertible acoustical laws, about which there should be absolutely no more discussion.

Schafhäutl then says:

From the student of nature, such an oracular speech in the name of science would certainly win a laugh.

He proposes to allow nature to speak for herself upon this interesting question. He then describes with great detail how he had made seven cavalry trumpets with internal dimensions all exactly alike; of thick brass, thin brass, lead, gypsum, and three of paper of different thicknesses; they were placed side by side on a convenient stand, and were blown by a most skillful professional trumpeter. He says:

What a difference in the tone quality! The most brilliant tone was given by the trumpet of brass 0.85 mm. thick. The tone of the trumpet of lead was heavy and dull, while the tone of the paper trumpets was papery and excited general laughter.

He describes many other experiments and opinions about reed instruments, violins, flutes, organs, the human voice, etc. The

study of this work led the writer to repeat some of Schafhäutl's experiments and to try others with organ pipes, the results of which will be given in some detail.

For a model an open organ pipe of wood was chosen, of the style usually supplied by Koenig for acoustical experiments. This pipe gives the tone $G_2 = 192$ complete vibrations—this is violin G, below middle C; the pipe is 5.8 cm. wide, 7 cm. deep, 78 cm. long and has walls 1 cm. thick. Four pipes having exactly the same internal dimensions as this wood pipe were made of common sheet zinc, the metal being about 0.5 mm. thick. Upon blowing one of the zinc pipes, the unexpected result was obtained that its pitch is more than two semi-tones of the musical scale lower than that of the wood pipe of the same dimensions; its pitch was found to be 164, and that of the other zinc pipes was nearly the same. The pipes are always blown on a windchest, under moderate pressure—$2\frac{1}{2}$ to $3\frac{1}{2}$ inches by the water gauge—which is automatically controlled.

While the zinc pipe is clearly sounding its fundamental tone, if it is very lightly touched on opposite sides by the thumb and finger, it immediately speaks the first overtone very clearly with no perceptible admixture of the fundamental; upon removal of the fingers the sound returns to the fundamental. The overtone thus obtained is not harmonic, its frequency being 2.06 times that of the fundamental; however, the pitch of both the fundamental and the overtone can be varied several vibrations per second by grasping the pipe in the hand and varying the pressure of the grasp.

If the pipe is firmly grasped in both

hands, just above the mouth, it speaks a mixture of the fundamental and the second partial, just mentioned and also a third partial whose frequency is 2.66 times that of the fundamental. By increasing the pressure of the hands on the outside of the pipe, the first and second partials become weaker, while the third becomes stronger till it is the real tone of the pipe; it is approximately the tone Bb, a fourth above the octave of the fundamental. These results are so conspicuous as to be almost startling, caused by the unmusical sound of the inharmonic partials; the tone quality varies as much as from a flute to a tin horn.

One of the zinc pipes was placed inside of a large pipe of zinc to form a double-walled pipe, with spaces 2 cm. wide between the walls; the outer wall was attached to the inner one only at the extreme bottom on three sides, but just above the upper lip plate on the front side. Attaching the outer pipe did not alter the pitch or quality in any noticeable degree. The double-walled pipe gives a full fundamental tone, $F_2 = 164$, without conspicuous overtones.

While the pipe is sounding continuously, water, at room temperature, is allowed slowly to run into the space between the walls. As this space is filling, the tone of the pipe changes conspicuously thirty or forty times; a few of these changes will be noted. When the water is 5 cm. above the lower lip, the pitch rises by 2 vibrations per second; when the water is 10 cm. high, the fundamental tone breaks, and the first overtone is clearly heard; at 11 cm. the fundamental is almost inaudible, the first overtone being loud; at 14 cm. the fundamental alone is heard, but with a pitch 6

vibrations sharper than at first. As the water rises the pitch begins to fall, and the overtone reappears, till, at a height of water of 28 cm., the two tones are both very distinctly heard, the fundamental having a pitch of 164 F_2, the same as at the beginning, and the overtone a pitch 2.13 times as great, about that of the tone $F_3\sharp$. At a height of water of 29.5 cm. the overtone is heard alone, at 31.5 cm. the fundamental only is heard; while at 33.5 cm. the two tones are mixed and are both clearly sounded. These alternations are again repeated, and as the water rises to a height of 46 cm. the fundamental begins to flatten, till, at 57 cm., its pitch is 158, that of the tone E_2, a semi-tone lower than at first. As the pitch of the fundamental falls, that of the overtone rises, and when the water stands 69 cm. high, the fundamental has a pitch of 160, the overtone 400, the ratio is 2 : 5, or the tones, instead of being an octave apart, are an octave and a third. The actual sounds are E_2 and $G_3\sharp$, and the two sounds from the one pipe are each as clear and distinct as the sounds from two separate pipes, as actual comparison has many times proved to various observers. As the water rises through the remaining 9 cm., there are several changes in quality; when the space is full of water the overtone, though present, is less intense and is not in such good tune.

This pipe, which has the dimensions of a wood pipe giving the tone G, has, when empty, the pitch F, and when filled with water the pitch is E; during the filling the pitch varies more than a semi-tone, first rising and then falling, while the changes in the quality of the tone are so astonishing

that they must be heard to be appreciated.

The pipe has been filled with sand, and it shows the same series of changes, though some of the tones seem to be more deadened than with the water filling, and it does not seem to be quite so sensitive to slight variations.

(Some photographic records of the variations in the sound waves coming from this pipe, and the pipe itself will be exhibited in another communication to the program of this meeting. The photographs show the distinctness of the changes that occur.)

It is, of course, well known that the pitch and even the quality of a pipe are influenced by the thickness of wall and condition of the inner surface; but that the properties of the pipe should be so profoundly altered by even slight changes entirely outside of the pipe was wholly unexpected, even with a pipe of the construction described. After the demonstration of these effects, one will surely admit that the quality of a wind-instrument may be affected by the material of its body to the comparatively limited extent claimed by the player. That the flute is more susceptible to this influence than other instruments is due to the fact that its tube is only from 0.2 to 0.3 mm. thick, that is, half as thick as the zinc walls of the experimental pipe. The cylindrical shape of the tube gives a mechanical stiffness which largely prevents the transmission of influences through the walls; nevertheless, it is conceivable that the presence or absence of a ferrule or of some support for a key might cause the appearance or disappearance of a partial tone, or put a harmonic partial slightly out of tune. (The idea of experi-

menting with a flute of rectangular cross-section occurred too late to be made use of at this time.)

The traditional influences of the different metals on the flute are consistent with the experimental results obtained from the organ pipe. Brass and German silver are usually so hard, brittle and stiff as to have but little influence upon the air column, and the tone is said to be hard and trumpet-like. Silver is heavier and softer, and adds to the mellowness of the tone. The much greater softness and density of gold adds still more to the soft-massiveness of the walls, giving an approach to the organ pipe surrounded by water, and permitting a greater influence of the walls upon the tone, and increasing the richness of tone by augmenting the fullness of the partials, as was the case with the organ pipe. That the partials from the gold flute are actually fuller than from other, is proved by the photographic comparisons of wave forms which are referred to in another communication.

Mere massiveness of the walls does not fulfill the desired condition; a heavy tube, obtained from thick walls of brass, has such increased rigidity as to produce an undesirable result. The walls must be thin, soft and flexible, and be made relatively massive by increasing the density of the material. A tube of pure platinum would best fulfill these conditions; a report upon the influence of such a tube may be made later.

The gold flute tube and the organ pipe surrounded with water are, no doubt, similar to the longer strings of the pianoforte which have such rich quality; these strings are wound or loaded, making them massive,

while the flexibility or "softness" is unimpaired. The organ pipe partly filled with water is like a string unequally loaded, its partials are out of tune and give a freak tone. The flute, unfortunately of necessity, is unequally loaded by its key mechanism, and this no doubt accounts for the fact always noticed by players, that certain tones are full while others are poor or dull in quality, or are liable to shrillness; the skillful player covers these defects by his art. This opinion is confirmed by the fact that the tone of flute tubes having no holes or keys is influenced by the manner of holding the tube in the hands; certain overtones are difficult to produce till the points of support of the tube have been shifted.

(The question has been answered to the writer's complete satisfaction by actual musical trials, extending over four years, with flutes of wood, hard rubber, glass, brass, German silver, silver and gold. The gold flute is, beyond all doubt, distinctly superior; its tone may be described as full, rich, less shrill when sounded loudly, and more liquid; the silver flute is more delicate, and certainly simpler in quality, which manifests itself as shrillness in the loud and high tones.)

The quantitative and photographic investigation of this question is not complete, but one result of general application seems conclusive. Perhaps the theory of Helmholtz has been very generally accepted, that all tones of the same quality, that is, belonging to the same register of any given instrument, have a characteristic set of harmonics, the proportional intensities of which remain constant. Visual and photographic observation of the wave forms from

many instruments shows that the overtones are certainly not harmonic in the sense commonly understood, and, moreover, the different notes in the scale of any one instrument are not similar in their composition. While a tone is being given with no variation that the ear detects, the partials are seen to be rapidly varying in phase, or intensity, or both. A slight change in the manner of blowing a wind instrument, which to the ear results merely in a change of loudness, completely alters the form of the wave. Instead of a characteristic series of harmonics, it seems that each instrument possesses rather a characteristic tone or tones, which is of constant pitch for all notes of its scale. This theory has been recently advanced by Meissner, from experiments with the phonograph. Such a characteristic tone for the flute would seem to be consistent with the rather anomalous conditions imposed by the stopper in the head-joint of the instrument.

The inadequacy of the former theory is clearly shown by the failure of many attempts to synthetically reproduce the characteristic tones of orchestral instruments, such as those by Helmholtz, Koenig and more recently by the Telharmonium.

A complete reply to the second part, "Why," of the question propounded for consideration has, by no means been given; but the first part of the question, we feel, has been conclusively answered: the effect of material upon tone quality of wind instruments certainly is not a fable.

Dayton C. Miller
Case School of Applied Science